State of volcanic hazard forecasting: needs, challenges and opportunities

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Image from JMA Himawari Satellite

Servicio Meteorológico Nacional

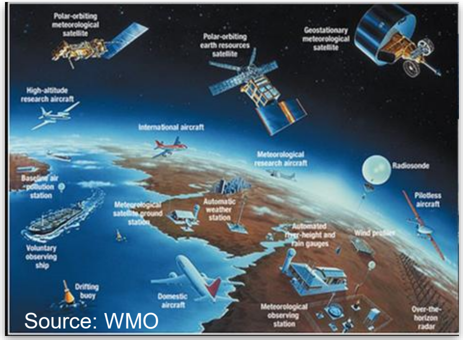
ISTITUTO NAZIONALE DI GEOFISICA E VULCANOLOGIA

unesco Intergovernmental Oceanographic Commission

World Weather Watch

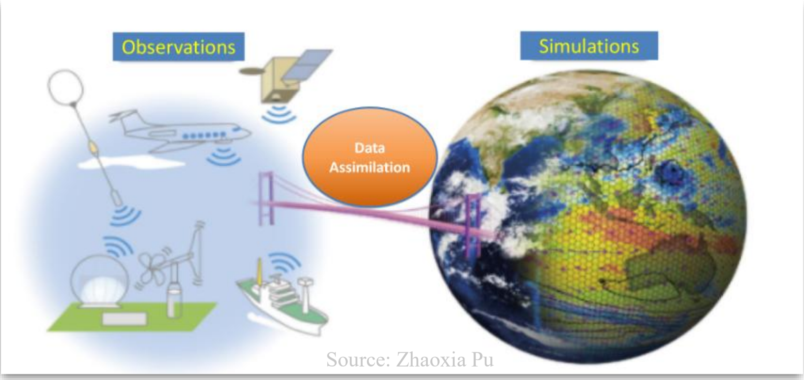
At the global level, the Meteorological and Hydrological Services (NMHS) share their data.

The **WMO Integrated Global Observation System (WIGOS)** integrates all the observations of the state of the atmosphere and ocean surface using land-based and space-based instruments.



The data is shared globally in a coordinated way through the **WMO Information System 2.0 (WIS 2.0).**

The data is used to assimilate to the global atmospheric models and shared to the NMHS coordinated by the **WMO Integrated Processing and Prediction System (WIPPS).**



Expert Team on Emergency Response Activities (ET-ERA) support WMO members on environmental emergency responses. Support coordinated by Regional Specialized Centres

Operational Volcano Watch

The **monitoring of the state of the volcanoes** is done by the **volcanological community.**

There are different degrees of progress in the monitoring of volcanoes in countries with volcanoes.

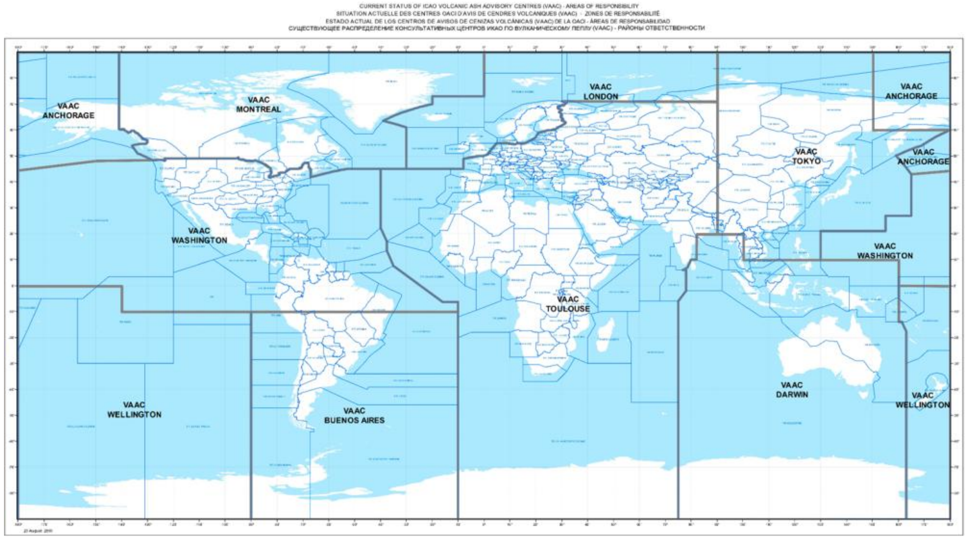
But there is **no global agreement on sharing data in real or near real** time, such as in meteorology with WMO Information System 2.0 (WIS 2.0)

There is **cooperation at local and regional level**.

An example is the **International Aviation Volcano Watch** (IAVW) from ICAO.

Joint collaboration for aviation safety the IAVW

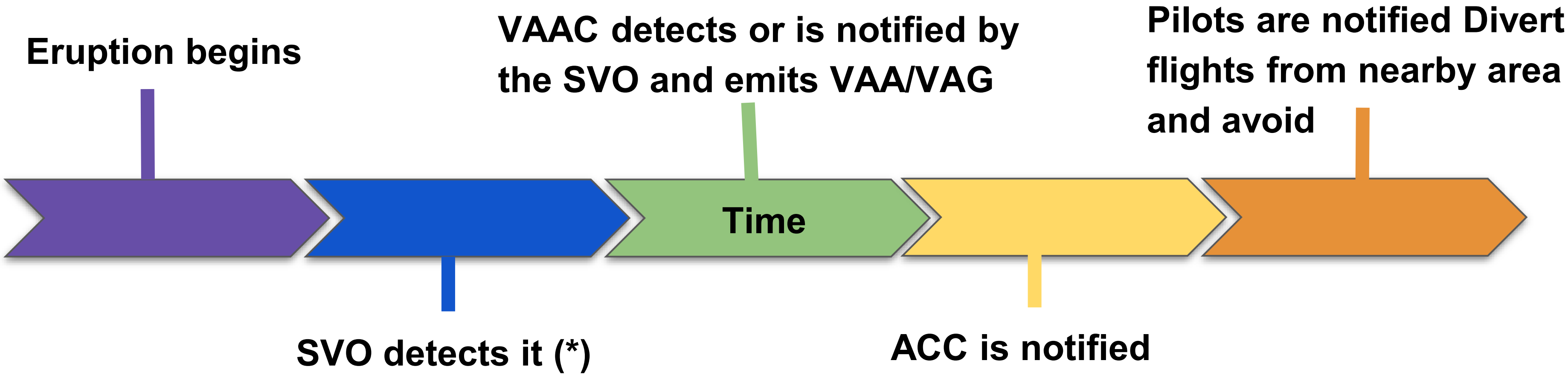
After the serious aircraft incidents in the 80's and 90's, the **meteorological and volcanological communities** start **cooperating** to contribute to the **Aviation Safety** on a regional basis through the **International Airways Volcano Watch (IAVW).**



Source:ICAO

Watch - IAVW Response Times

Aircraft at cruise level FL350-FL450 (~10-12 km) fly at around 900 km/h (i.e **~15 km in 1 min**).



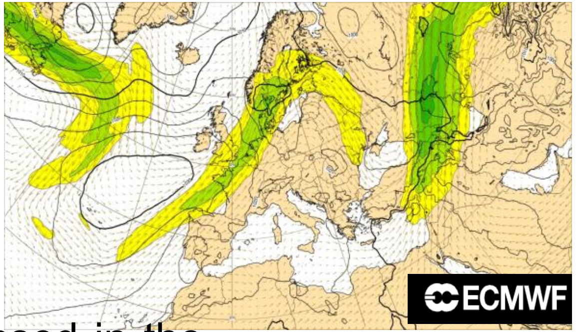
(*) it depends on the country.

VAAC has 20 minutes since reliable information is received to produce the first VAA/VAG (i.e **300 km flight distance**)

If we depend on satellite data the warning time depends on the latency of receiving the data. Example GOES has a latency of 20 min.

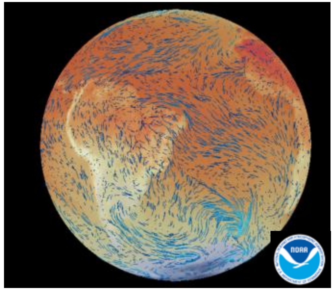
It is **important to reduce the notification time**. **SVOs** have a **key role in this**, as they have the data in situ and information on precursory signals of unrest.

Regional ash dispersion and deposition forecasting - meteorological contribution



Ash dispersion and deposition modeling requires **global collaboration** as the models are initialized with global meteorological models.

The results of **global meteorological modeling** can be accessed in the form of data or graphics depending on the center providing them. Dispersion modeling, needs meteorological model data, so it is important to have access to this information in real time.



In some cases, satellite data is used to assimilate and better estimate the state of the plume

Challenges: more weather models should be open and public for emergency agencies (NMHS, SVOs) so as not to generate a dependency in case a country stops providing access.

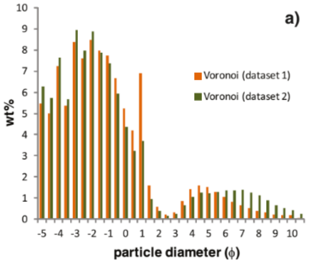
Regional ash dispersion and deposition forecasting - volcanological contribution

In operational modeling, run time is key and that is why 1D models representing the emission are often used.

These models require **eruptive source parameters (ESP)** such as the location of the emission center, the particle size, the particle density, the top height, the onset, the expected duration of the emission.

Important initiatives of ESP:

- Mastin et al. (2009) with the USGS database and now hosted by BGS.
- IVESPA database (Aubry et al., 2023).



Bondaonna et al., (2015)

Challenges: More contributions are needed to better characterize each volcano.

Quality of the forecasts - verification and improvements

The quality of forecasts is key for users to be able to trust them.

Satellite estimates on ash mass load are produced by the space agencies, which is the integration of the fine ash mass per unit area.

Ground deposit information is obtained by field campaigns or in situ instrumentation.

More observational information is needed to be share to validate three-dimensional ash concentration and ash deposit.

Challenge: a global strategy to observe, share data and validate model results is necessary.

One Volcano, Many Hazards: From the Atmosphere to the Ground

A single eruption is a **complex, multi-hazard event**. The very same explosive process that powers the ash cloud also unleashes a series of immediate and extremely dangerous phenomena on and around the volcano itself.

1. Eruptive Column & Ash Cloud:
2. Pyroclastic Density Current (PDC):
3. Ballistic Projectiles
4. Lahar / Debris Flow

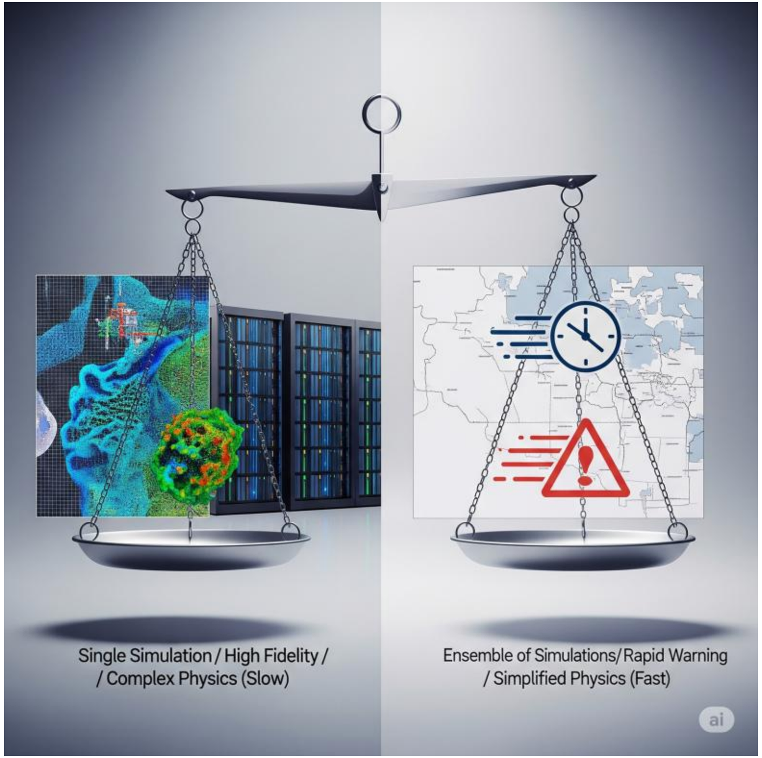
For **most of them**, differently from ash dispersal, represent **local hazards**, without common/global protocols.

The Forecaster's Dilemma: Speed vs. Accuracy Under Uncertainty

One of the core challenge for any volcanologist involved in hazard assessment (in particular when it's "short-time"):

- On one hand, we have sophisticated, **complex 3D physics-based models** that capture the complex reality of these flows. They are accurate and give us deep scientific insight, but they are computationally expensive—taking hours or days to run. They are better suited for scientific understanding, and possibly for long-term planning.
- On the other hand, an effective early warning requires an answer in minutes or hours, not days. This forces us to use **simplified models or pre-computed scenarios** that prioritize speed over physical completeness.

This is not a failure of modeling; it is a necessary compromise. The art and science of operational forecasting lie in **choosing the right tool for the job**.



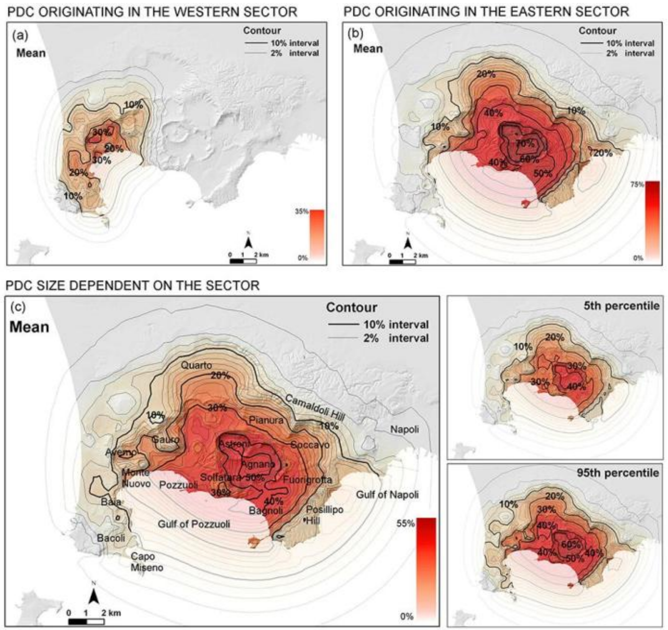
PDCs - The Race for a "Good Enough" Forecast

For long-term planning, like at Campi Flegrei, **simplified 'box models' allowed to run thousands of scenarios to build a probabilistic hazard map**. This was state-of-the-art for its time.

Today, complex 3D models can simulate an explosive eruption with incredible detail, but a single run takes hours or days on an HPC cluster. This is invaluable for science, but far too slow for early warning.

In the shift from long-term to short-term assessment, we gain crucial information—typically the eruption's location. This reduces uncertainty, but not enough for 3D models.

The sweet spot for EWS can be depth-averaged models. They offer a powerful compromise, allowing us to run hundreds of physically realistic scenarios in hours, not days. We can generate probabilistic forecasts based on the latest monitoring data.



Bevilacqua, Andrea, et al. "The effects of vent location, event scale, and time forecasts on pyroclastic density current hazard maps at Campi Flegrei caldera (Italy)." *Frontiers in Earth Science* 5 (2017): 72.

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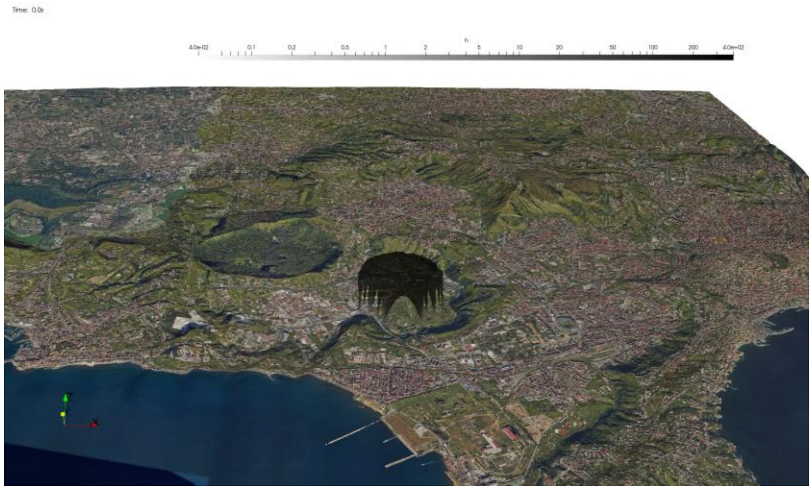
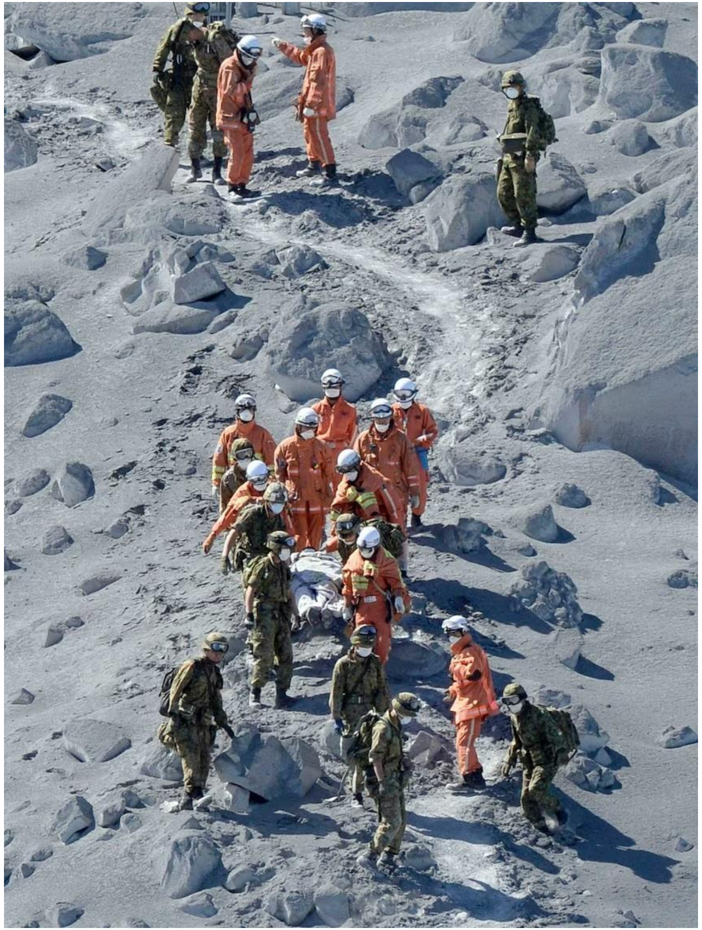


Depth-average model: numerical simulation of a PDC generated by a collapse. 100k cells, horizontal resolution 50m, time to solution (150s): 21.7s.

Ballistics - Beyond Simple Physics

For explosive eruptions, ballistics are a primary hazard. The Ontake eruption was a tragic reminder of their lethality, especially during unexpected phreatic events.

A phreatic eruption took place at Mount Ontake on September 27, 2014, killing 63 people. Nearly all fatalities were due to ballistic impacts. Our classic hazard maps rely on **simple models of pure ballistic trajectories**. But this is an oversimplification. The real trajectories, also for meter-sized blocks, can be coupled with the complex dynamics of the explosion and, crucially, the shape of the crater.



Japan Self-Defense Force (JSDF) soldiers and firefighters carry an injured person off Mount Ontake. (Reuters: Kyodo)

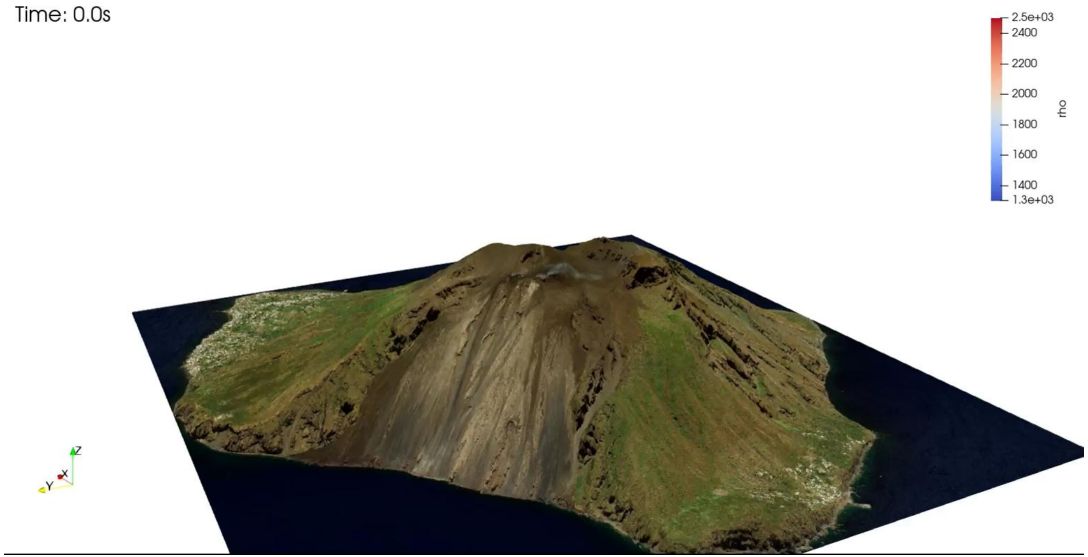
Ballistics - Beyond Simple Physics

At Stromboli, a recent multidisciplinary project has shown that it is possible, with the use of drones or satellite images, to rapidly **update the models of crater topography**.

And, as soon a new high-resolution DEM is available, ballistic **scenarios can be updated in just a few hours**.

The next frontier for early warning is to automate this process.

We need a system that integrates new DEMs and monitoring data to update probabilistic ballistic hazard maps in near real-time, especially for a paroxysmal eruption EWS.



Ballistic simulation done with OpenPDAC on 144 cores. Time -to solution is approx 3hours.

Cascading Hazards - Craters
Collapses and pyroclastic avalanches

The hazard does not end with the eruption. The volcano's edifice is altered, with unconsolidated deposits creating **new, 'secondary' threats**. Lahars are a classical example.

Stromboli village, May15, 2025. From Facebook

Cascading Hazards - Craters Collapses and pyroclastic avalanches

The hazard does not end with the eruption. The volcano's edifice is altered, with unconsolidated deposits creating **new, 'secondary' threats**. Lahars are a classical example. The recent Etna crater collapse is another perfect example – luckily, no one was hurt.

This highlights the need for **continuous stability monitoring and modeling**. Updated DEMs are not just for ballistics; they are critical for assessing the stability of the volcanic edifice.

Mount Etna, June 2, 2025. From Reddit.

Cascading Hazards - Craters Collapses and pyroclastic avalanches

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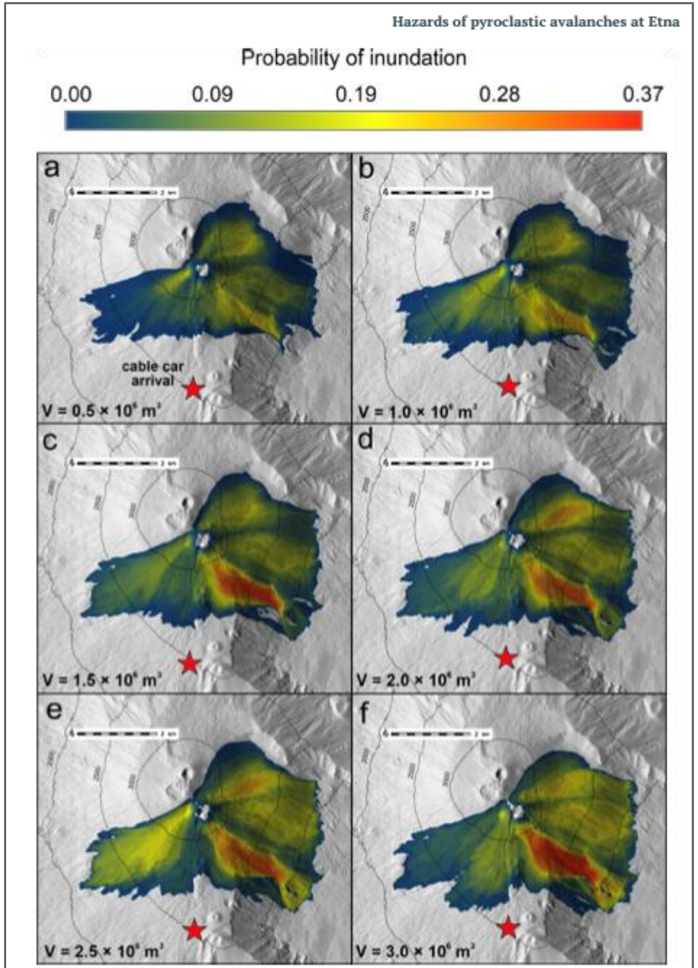
Also for this kind of hazard, **depth-averaged models allows for rapid updates of hazard maps**.



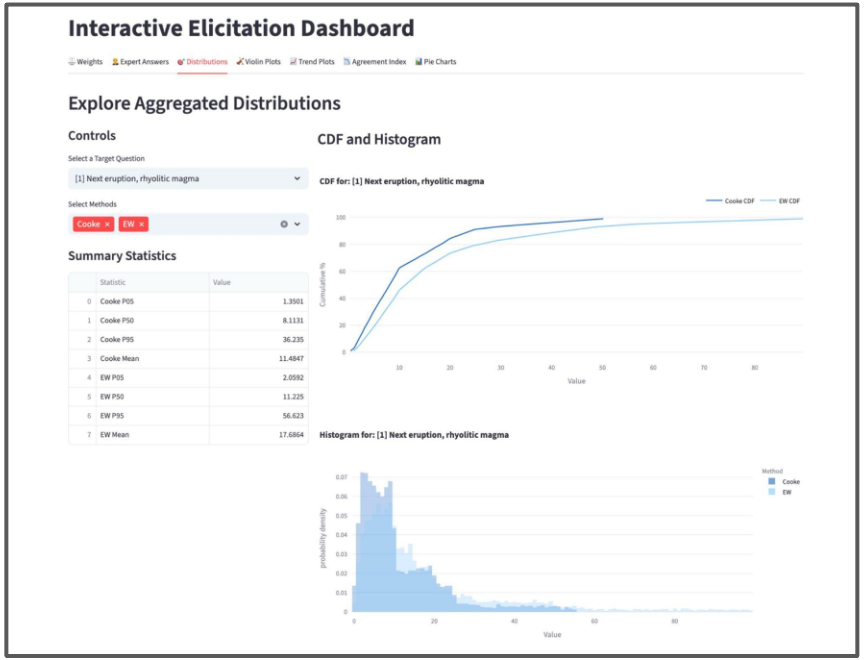
Zuccarello, Francesco, et al. "Dynamics and hazards of pyroclastic avalanches at Etna volcano (Italy)." *Annals of Geophysics* 68.1 (2025): V103-V103.

Quantifying Input Uncertainty: The Role of Expert Elicitation

So far, we've focused on the models. But a model is only as good as its inputs. What do we do when we have **high uncertainty in key parameters** like potential eruption volume or landslide location?

When direct data is insufficient, we must formally **quantify the judgment** of the scientific community. This can be done through **Expert Elicitation**, a structured process that has been used routinely in places like Iceland to define probabilities for eruptive scenarios.

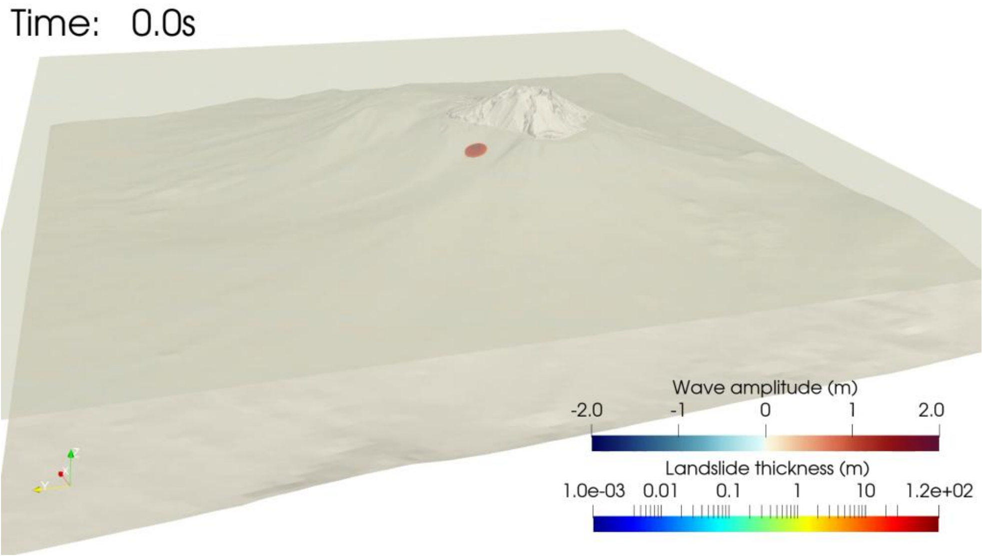
This provides a **traceable and defensible way to define the uncertainty on our inputs**, which is critical for credible hazard assessment.



From the Flank to the Wave: An Elicitation-Informed Forecast

In a recent project, funded by the Italian Civil Protection, we used Expert Elicitation to **ask experts to assign probabilities to different landslide volumes and source locations** on the Sciara del Fuoco at Stromboli.

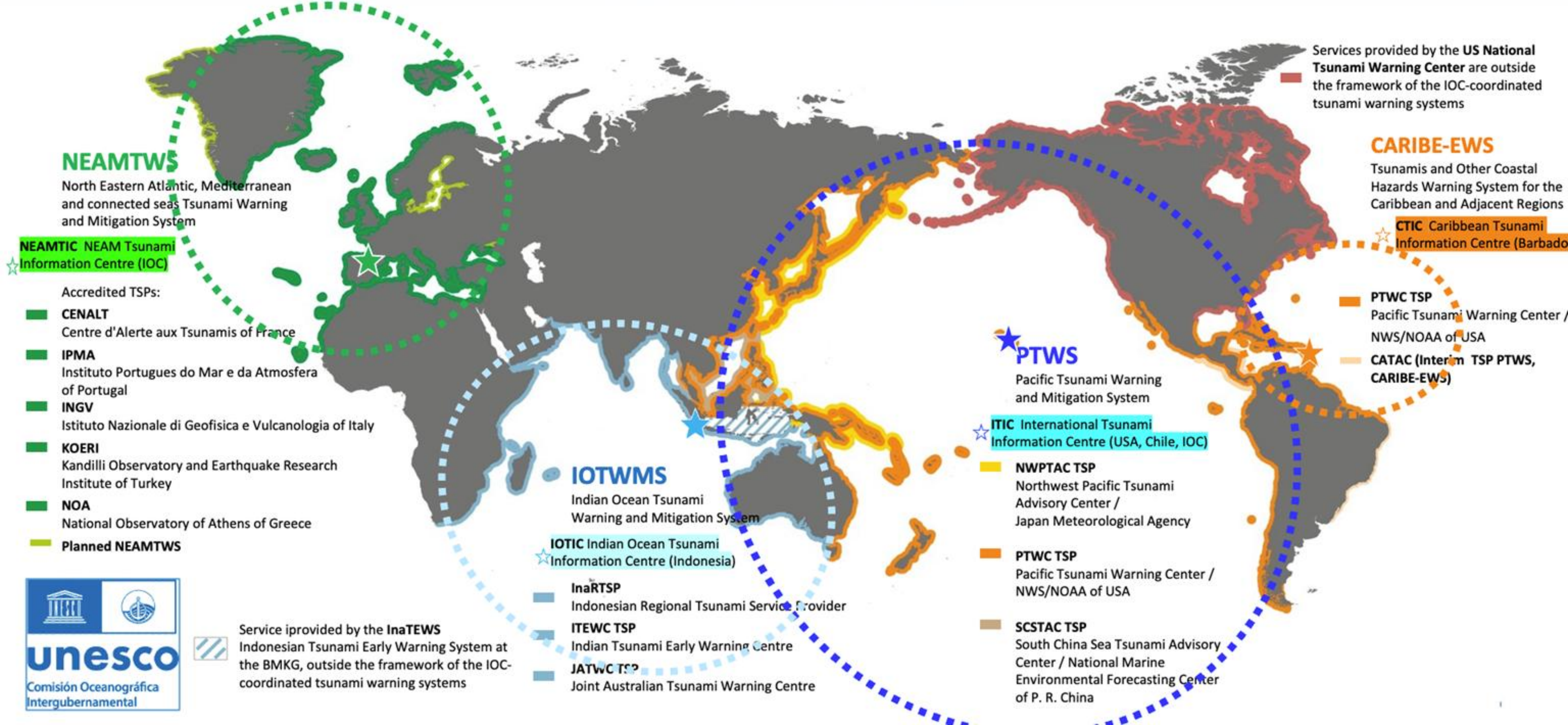
The resulting samples were used to process a large number of model runs, creating the first **probabilistic tsunami inundation maps** for the island based on a formal expert elicitation. This simulation shows one of those scenarios. By combining many such runs, we can tell the community not just if a location might be flooded, but the probability of it being flooded, which is a much more powerful piece of information for planning and warning.
The outcomes of the modeling exercise can also be used to design evacuation areas to use with early warning systems.



GLOBAL TSUNAMI WARNING AND MITIGATION SYSTEM

Intergovernmental Oceanographic Commission of UNESCO

2025   www.ioc-tsunami.org



Each ICG (Intergovernmental Coordination Group) …

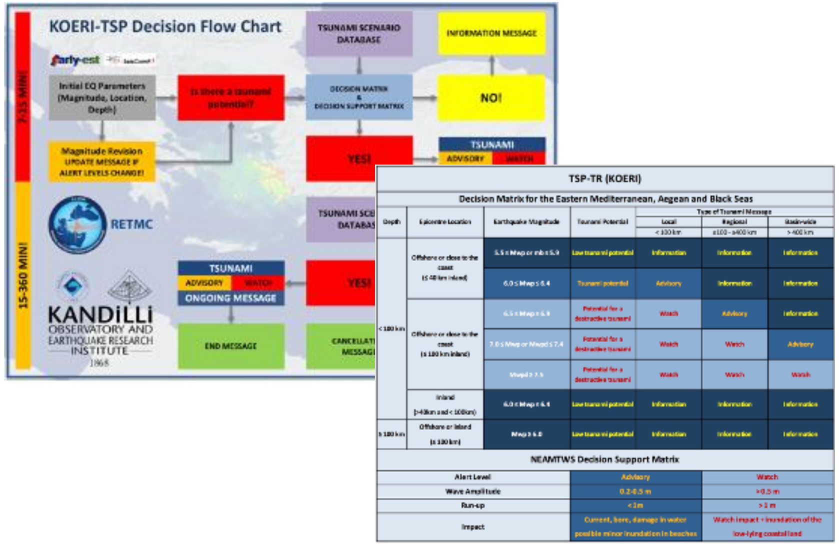
Early Warnings for All

- Includes Working Groups on
  - Hazard & Risk Knowledge
  - Operations (detection, observation, monitoring, analysis and forecasting)
  - Warning dissemination and communication
  - Preparedness and response capabilities
- Regular Tsunami Exercises
- voluntary, performance-based community Tsunami Ready Recognition Programme

… a science-policy interface
with more than a century of cumulative history …

Tsunami Ready

NTWC/TSP Decision Support System



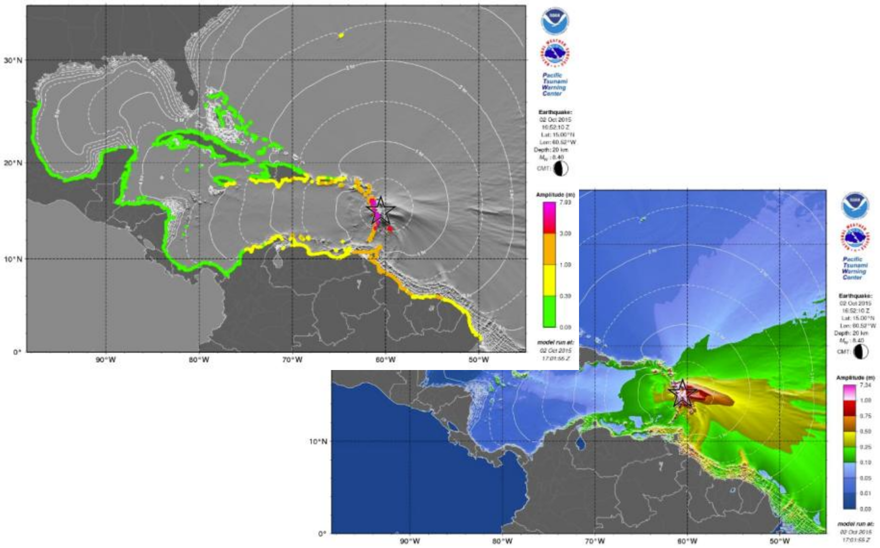
TSP-TR (KOERI)

Decision Matrix for the Eastern Mediterranean, Aegean and Black Seas

Depth	Epicentre Location	Earthquake Magnitude	Tsunami Potential	Type of Tsunami Message: Local < 100 km	Regional ≥100 – ≤400 km	Basin-wide > 400 km
< 100 km	Offshore or close to the coast (≤ 40 km inland)	5.5 ≤ Mwp or mb ≤ 5.9	Low tsunami potential	Information	Information	Information
		6.0 ≤ Mwp ≤ 6.4	Tsunami potential	Advisory	Information	Information
	Offshore or close to the coast (≤ 100 km inland)	6.5 ≤ Mwp ≤ 6.9	Potential for a destructive tsunami	Watch	Advisory	Information
		7.0 ≤ Mwp or Mwpd ≤ 7.4	Potential for a destructive tsunami	Watch	Watch	Advisory
		Mwpd ≥ 7.5	Potential for a destructive tsunami	Watch	Watch	Watch
	Inland (>40km and < 100km)	6.0 ≤ Mwp ≤ 6.4	Low tsunami potential	Information	Information	Information
≥ 100 km	Offshore or inland (≤ 100 km)	Mwp ≥ 6.0	Low tsunami potential	Information	Information	Information

NEAMTWS Decision Support Matrix

Alert Level	Advisory	Watch
Wave Amplitude	0.2-0.5 m	>0.5 m
Run-up	< 1m	> 1 m
Impact	Current, bore, damage in water possible minor inundation in beaches	Watch impact + inundation of the low-lying coastal land



National Tsunami Warning Center (NTWC)
A center operated by a Member State that has the authority by law or otherwise to issue tsunami warnings for the coasts of that Member State.
Ideally, an NTWC should have some technical capability to aid in decisions.

Tsunami Service Provider (TSP)
A center like PTWC, NWPTAC (JMA), SCSTAC (China), CATAC (Nicaragua) with the capability to detect and assess tsunami threats over a large region, and that has been accepted by the ICG to disseminate their threat assessment to other Member States

Gaps in the traditional TEWS

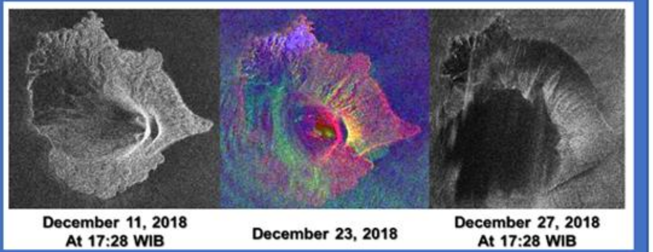
Palu and Sunda Strait Events in 2018

Palu Tsunami, 28 Sep 2018

- Deaths - 2,100; Missing 680; Injured 4,612; and Displaced 78,994
- Complex Event – Strike Slip Earthquake, Extensive Liquefaction, Coastal / Submarine Landslides, Bay
- Tsunami Warning issued by BMKG in 5 Minutes
- Tsunami Waves of Several Metres arrived within 2 – 4 minutes
- No time for communities to receive official warning
- IOC-UNESCO International Tsunami Survey Teams

Sunda Strait Tsunami, 22 Dec 2018

- Deaths - 430; Missing 128; Injured 1,459; and Displaced 5,695
- Caused by flank collapse due to eruption of Anak Krakatau volcano
- No Tsunami Early Warning issued
- Tsunami waves arrived in succession following the eruptions patterns, and avalanches.
- Tsunami confirmed only by recognizing wave anomaly at near-by tide-gauges



Challenges in the Upstream

- Gaps in Hazard Assessment
- "Uncertainties" in tsunami early warning
- Warning systems not suited for "near-field", "atypical" sources
- Failure of tsunami early warning chain

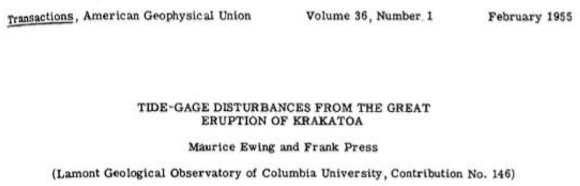
Lessons Learnt in the Downstream

- False sense of security in the community
- Sustained preparedness, awareness, and education in local context
- Importance of evacuation plans, routes and shelters
- Importance of internalizing past experience
- Self-Evacuation is the key to safety - "near field"

Source: R. Bailey (former Head of the IOTWMS Secretariat) @ JRC-Ispra Workshop (2022)

Gaps in the traditional TEWS

Hunga Tonga–Hunga Ha‘apai (HTHH) Example

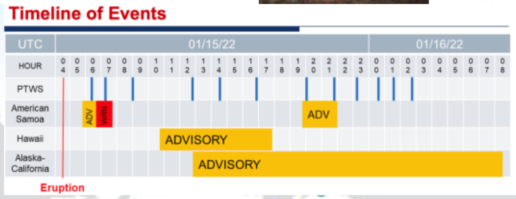

Transactions, American Geophysical Union Volume 36, Number 1 February 1955

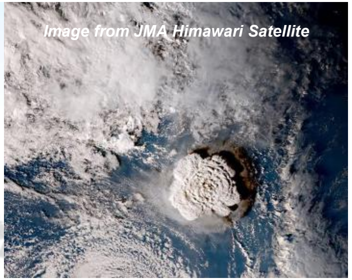
TIDE-GAGE DISTURBANCES FROM THE GREAT ERUPTION OF KRAKATOA

Maurice Ewing and Frank Press

(Lamont Geological Observatory of Columbia University, Contribution No. 146)

- Based on sea level data, the Tonga's NTWC issued a tsunami warning at 4:31 UTC (17 min after the explosion)
- Japan and Australia had SOPs for tsunamis generated by volcanoes and issued national tsunami warnings
- The PTWC in Hawaii initially had issues with earthquake-based tsunami warnings systems, but managed to eventually issue an initial threat bulletin for the entire Pacific Ocean at 6:23 UTC
- Fiji, Vanuatu, New Zealand, and Samoa NTWCs issued tsunami warnings at 6:35, 7:35, 7:41 and 8:45 UTC, respectively
- ITIC organized 3 post-event briefings and Member State survey of responses



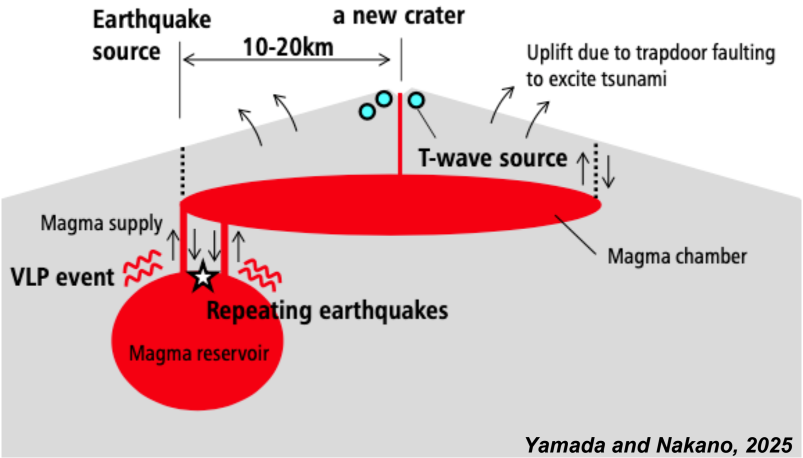


MAXIMUM TSUNAMI AMPLITUDES REPORTED by PTWC on 15 January 2022

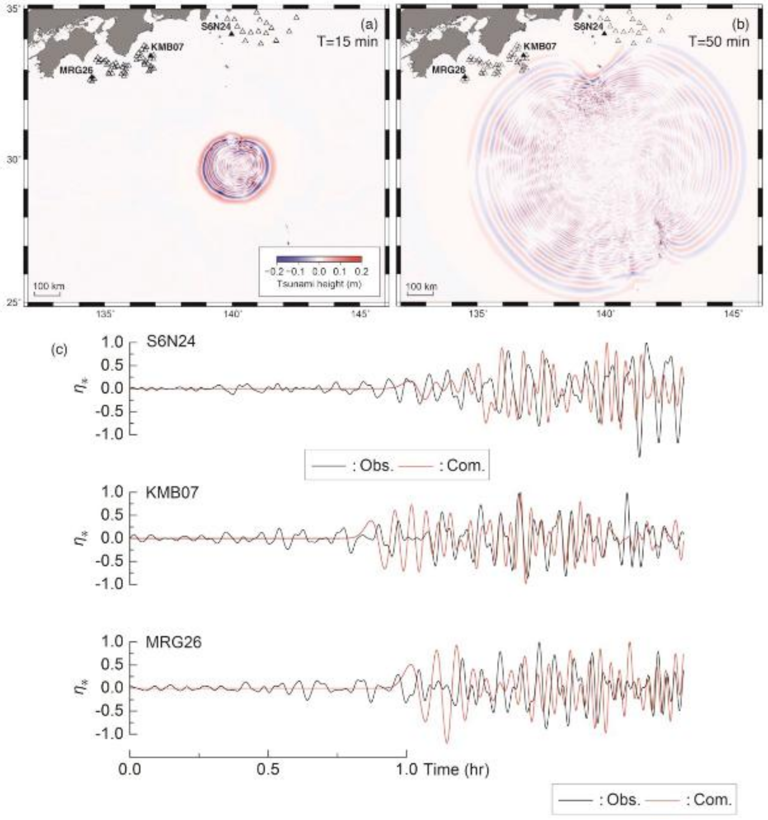
Source: R. Bailey (former Head of the IOTWMS Secretariat) @ JRC-Ispra Workshop (2022)

Gaps in the traditional TEWS

Sofugan Volcano (Japan, 2023)



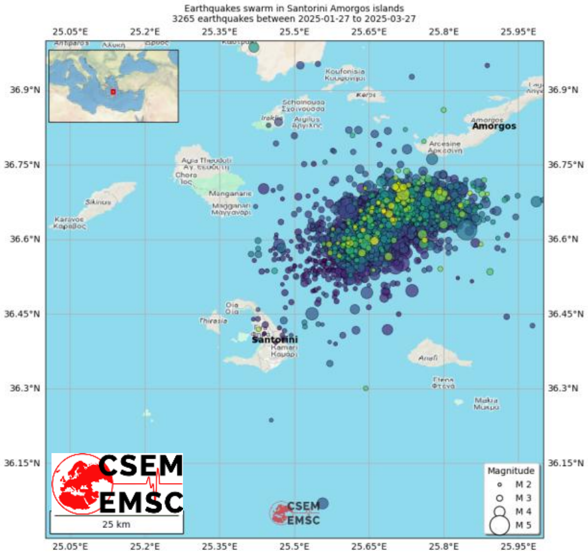
On 8 October 2023, mysterious tsunamis hit Izu Islands and southwestern Japan, reaching up to 60 cm in height, although only small-to-moderate seismic events (>10 events with mb 4–5) were reported in the region. Tsunami waves were intermittently produced by repetitive source events for approximately 1.5 hr, and the wave amplification happened because the inter-event times matched the wave periods (Sandanbata et al., 2023).

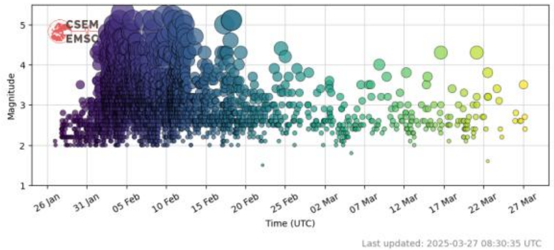


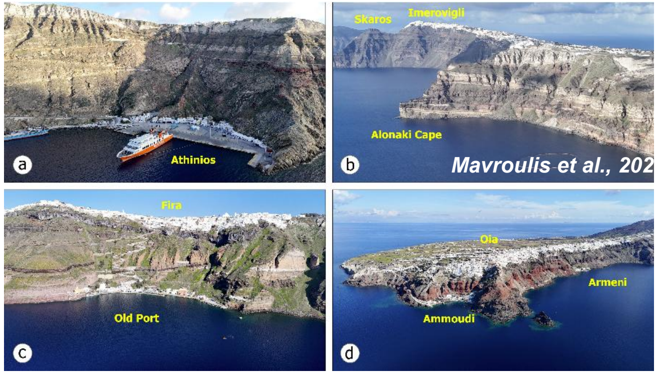
Fujiwara et al, 2023

Gaps in the traditional TEWS

Santorini–Amorgos Earthquake Swarm (2025)







In early 2025, the Santorini–Amorgos area (Aegean Volcanic Arc, Greece) experienced a seismic swarm, with dozens of $M \geq 4.0$ earthquakes and a maximum magnitude of $M = 5.2$ (Mavroulis et al., 2025).

?

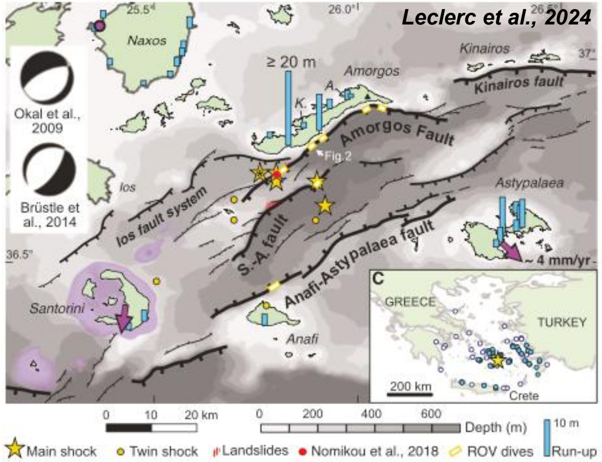
Eruption…

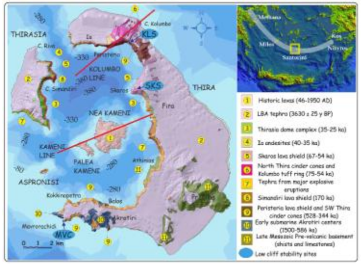
An earthquake with a larger (M>6) magnitude…

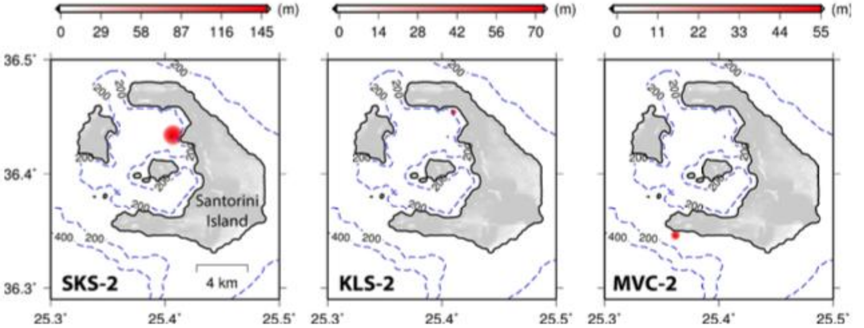
Collapse of caldera cliff…

Gaps in the traditional TEWS

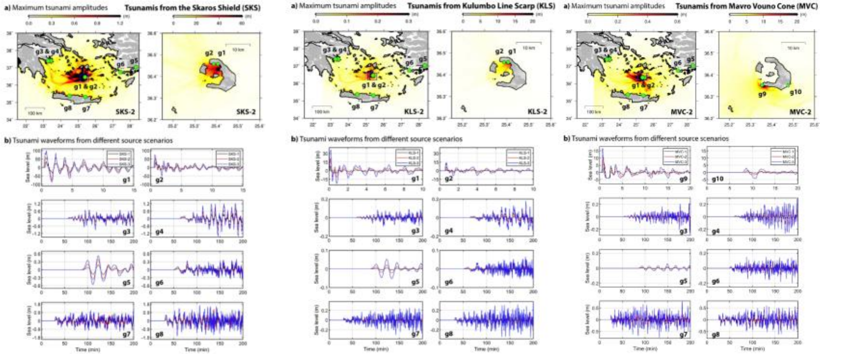
Santorini–Amorgos Earthquake Swarm (2025)







Necmioğlu et al., 2023

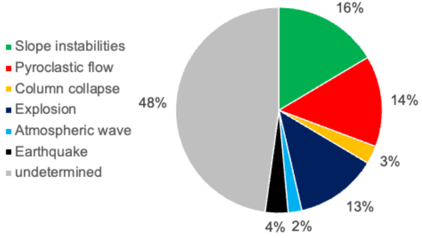


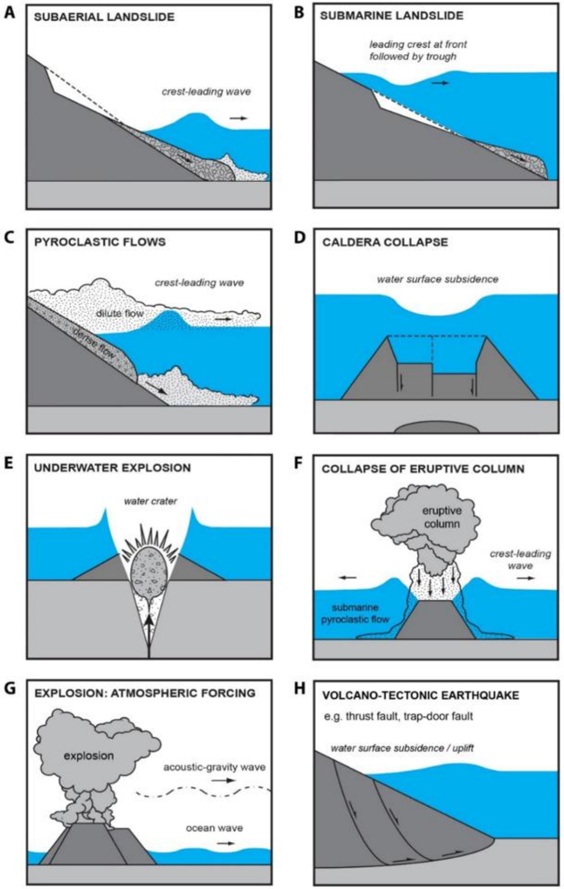
SKS scenarios can produce more than 60 m of tsunami amplitudes within the interior coasts of the Santorini Island. In the far-field area (coasts of Greece and Turkey), the tsunami amplitudes can be larger than 1.2 m.

In the case of KLS scenarios, the threat appears to be mostly in the near- field, with a tsunami capable of causing large destruction in almost all of the Santorini Island's interior coasts with waves larger than 5 m, as well as in the north part of the coast with waves as high as 20 m. Such phenomena could lead to the complete destruction of the Athinios Ferry Port at the bottom of the caldera, main port of Santorini, located approximately 10 km from Fira.

Even though the MVC scenarios result in minimum impact on the interior coastlines of the Island and negligible waves in the far-field coasts, the waves can be as high as 20 m in the near-field and thus should be considered as major hazards for local communities.

Tsunami sources in volcanic setting





Schindelé et al. (2024), modified from Paris et al. (2014)

Source: R. Paris

		Source mechanisms of volcanic tsunamis							
		Gravitational		Eruptive				Tectonic	
Type of eruption	***Example***	Subaerial landslide	Submarine landslide	Underwater explosion	Column collapse	Pyroclastic flow	Atmospheric forcing	Caldera collapse	Volcano-tectonic earthquake
Phreatomagmatic eruption in shallow waters	*Karymsky Lake 1996* *Myojin-sho 1952*								
Explosive paroxysm of a coastal stratovolcano	*Stromboli 2002* *Tinakula 1971*								
Explosive eruption with dome growth and collapse	*Montserrat 2003* *Paluweh 1928*								
Plinia eruption forming a subaerial caldera	*Tambora 1815* *Aniakchak 3.5 ka*								
Plinian eruption forming a submarine caldera	*Krakatau 1883* *HTHH 2022*								

Tsunami source	Surface area (km²)	Volume (km³)	Flux (m³/s)	Wave heights (m)		
				< 20 km	20 - 100 km	> 100 km
Subaerial landslide	10^{-2} - 10^{3}	10^{-1} - 10^{2}	10^{5} - 10^{6}	5 - 100	< 15	< 5
Submarine landslide	10^{-1} - 10^{4}	10^{-1} - 10^{2}	10^{5} - 10^{6}	< 20 ?	< 10 ?	< 5
Underwater explosion	10^{-2} - 10^{1}	10^{-3} - 10^{0}	10^{8} - 10^{9}	< 20 ?	< 3	< 1
Column collapse	10^{0} - 10^{2}	10^{0} - 10^{2}	10^{5} - 10^{8}	?	< 20	< 5
Pyroclastic flow	10^{-2} - 10^{3}	10^{-1} - 10^{2}	10^{5} - 10^{8}	< 10	< 5	< 2
Caldera collapse	10^{0} - 10^{2}	10^{0} - 10^{2}	10^{3} - 10^{5}	< 5 ?	< 2 ?	< 1 ?
VT-tectonic earthquake	10^{1} - 10^{2}	10^{-1} - 10^{1}	10^{6} - 10^{9}	< 20 ?	< 10	< 3

unesco
Intergovernmental Oceanographic Commission

Addressing the challenge:
PTWC Hunga Tonga–Hunga Ha‘apai (HTHH) Procedures

- PTWC will be **alerted by tsunami waves arriving at the Nuku`alofa gauge or any other nearby gauge (~15 minutes after volcanic event)**
- PTWC will immediately **call the Tonga NTWC (Met Office) to report the waves**
- The first arrival time and tsunami amplitude at the Nuku`alofa gauge will be measured and recorded
- An **initial PTWS Threat Message will be issued, nominally for all coasts within 3 hours tsunami travel time, that includes:**
  - ETAs at the normal PTWS warning points and sea-level gauges based on the standard sqrt(g*h) computation
  - An amplitude forecast at sea-level gauges based on scaling the observed 15 January 2022 amplitudes with the currently observed amplitudes
  - Observed amplitudes at sea-level gauges
- An **SMS is automatically sent with the first message to alert key government officials in Tonga**
- Dissemination will be through all the normal ways that current PTWS messages are sent: GTS, Email, AFTN
- The **tsunami will be monitored on sea level gauges as it propagates and additional measurements will be made**
- Based on the additional tide gauge readings:
  - The forecast will be adjusted if necessary
  - The threat area will be expanded or contracted
- **Messages will be issued at least once an hour, expanding the threat area if needed, until the threat has passed**
- **A final Threat Message will be issued when readings on all (or most) gauges are below 0.3m amplitude and when no further impacts above 0.3m are anticipated elsewhere.**

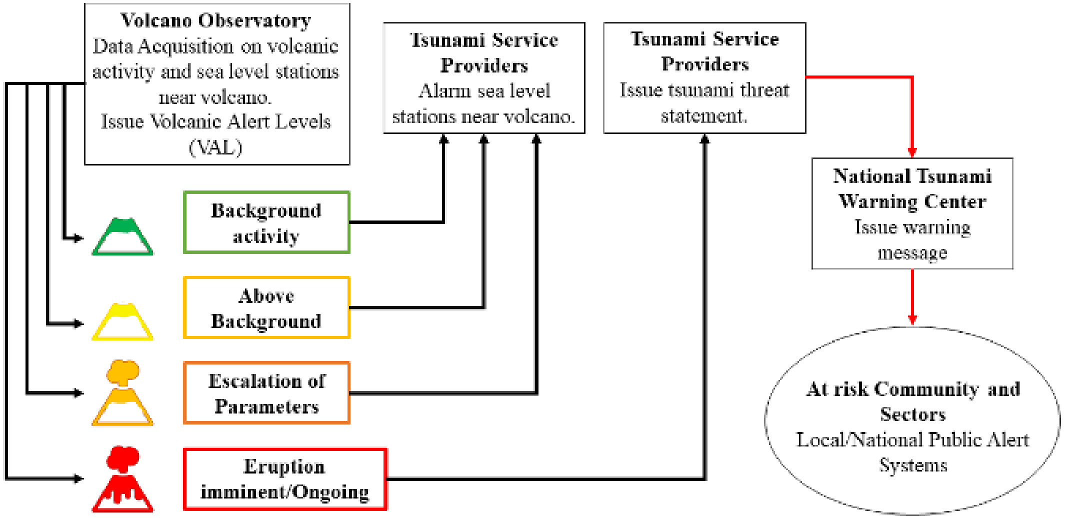
Addressing the challenge:

Volcano Observatory Notice for tsUnami Threat (VONUT)

based on Volcano Notice for Aviation (VONA) …

- please see the poster -

Alerting on Tsunamis Generated by Volcanoes



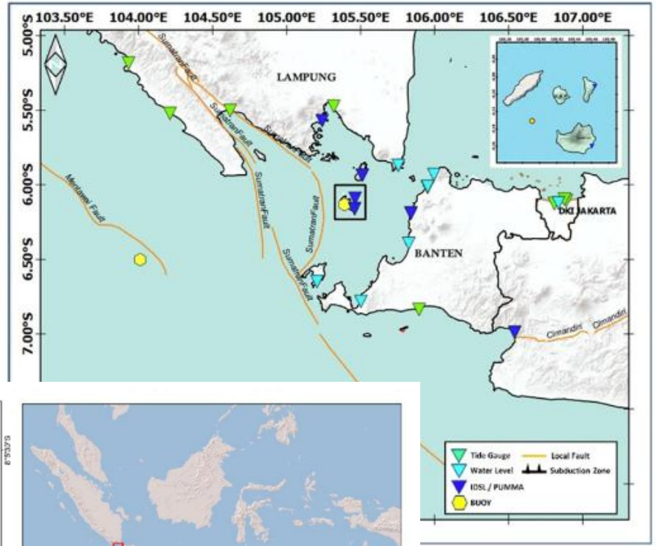
(1) VOLCANO OBSERVATORY NOTICE FOR TSUNAMI THREAT-VONUT	
(2) Issued: Universal (Z) date and time (YYYYMMDD/HHMMZ):	20230323/1330Z
(3) Volcano: Name and number (per Smithsonian database at http://volcano.si.edu/):	Pelée 360120
(4) Current Aviation Colour Code: **GREEN, YELLOW, ORANGE, OR RED** in upper case bold font	Red
(5) Previous Aviation Colour Code: Lower case font, not bold	Orange
(6) Source: Name of Volcano Observatory (volcanological agency)	1) Volcanological and Seismological Observatory of Martinique (OVSM)
(7) Notice Number: year-VONUT number (e.g. 2010-1)	2025-1
(8) Volcano Location: Latitude, longitude in NOTAM format (deg min N or S deg min W or E, e.g. 4701N 0513W)	1448N 6110W
(9) Area: Regional descriptor	Martinique Island, WI
(10) Summit Elevation: nnnnn FT (nnnn M)	4501 FT (1372 M)
(11) Volcanic Activity Summary: Concise statement that describes activity at the volcano. If known, time of onset and duration of eruptive activity are specified (local and UTC).	Increase in seismic activity, including tremors and several M>4 earthquakes at shallow depth, fissure openings, increase in fumarolic activity, important deformation of ca. 5 cm since the last 4 weeks on the southwestern flank.
(12) Sea sector of the impact (North/South, East, West) "UNKNOWN" if no data available	Most probably the south-western flank of Mount Pelée
(13) Name of the sea (Caribbean, Atlantic, Dominique Channel) "UNKNOWN" if no data available	Most probably the Caribbean Sea

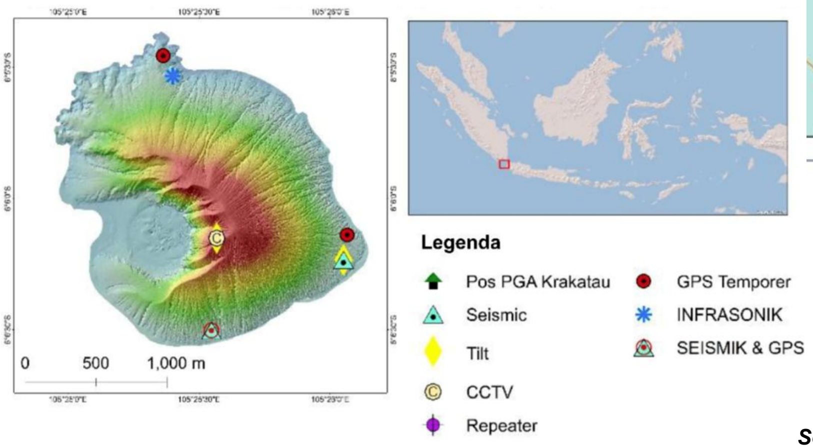
VONUT was tested during CARIBE WAVE 2023 and will be again tested during CARIBE WAVE 2026.

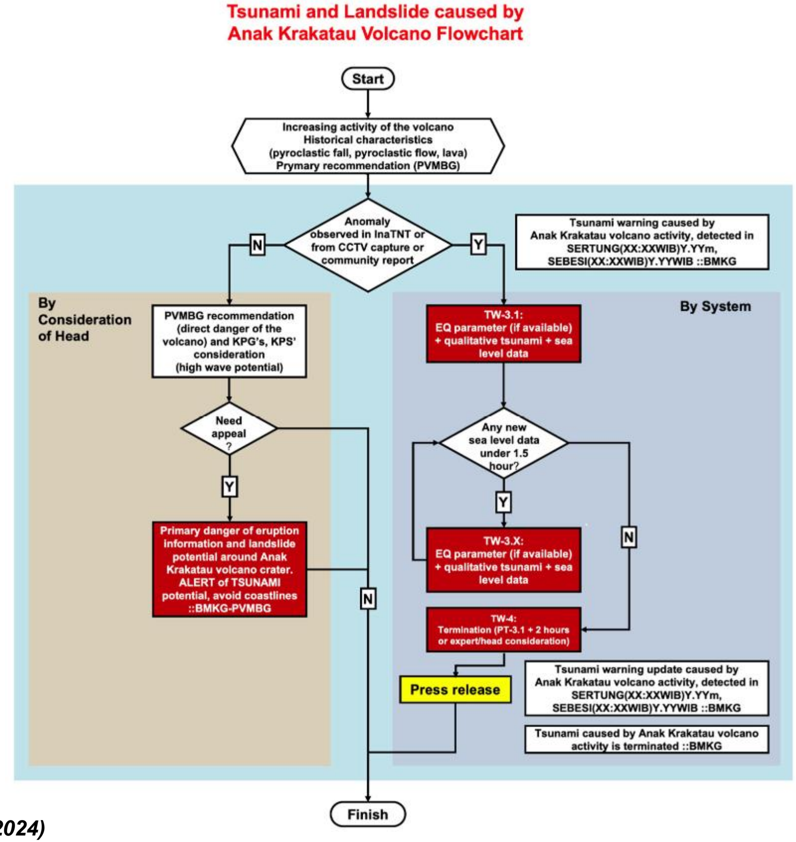
Clouard, V., von Hillebrandt–Andrade, C., McCreery, C. et al. Implementation of tsunami warning procedures in the Caribbean in case of a volcano crisis: Use of a Volcano Notice for tsUnami Threat (VONUT). Bull Volcanol 86, 18 (2024). https://doi.org/10.1007/s00445-023-01702-8

Addressing the challenge:

Anak Krakatau Volcanic Tsunami Warning System





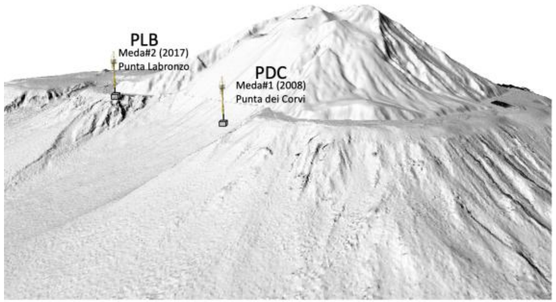


Source: Schindelé et al. (2024)

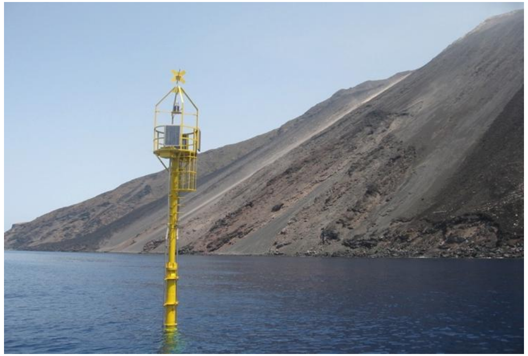
Addressing the challenge:

Stromboli Tsunami Early Warning System

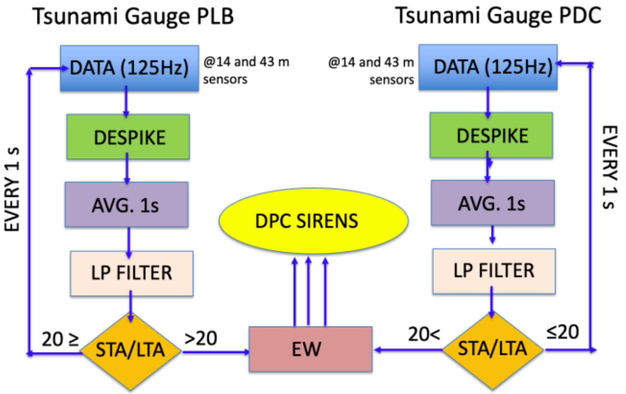
The Tsunami Early-Warning System



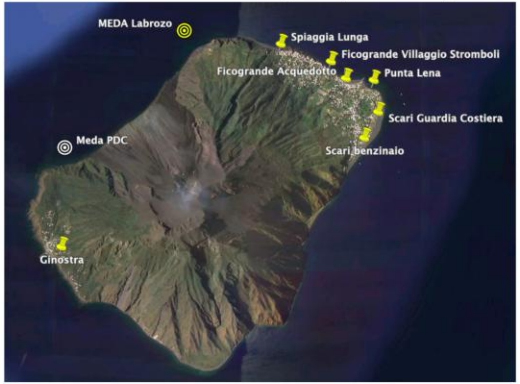
The system infrastructure is based on two elastic beacons



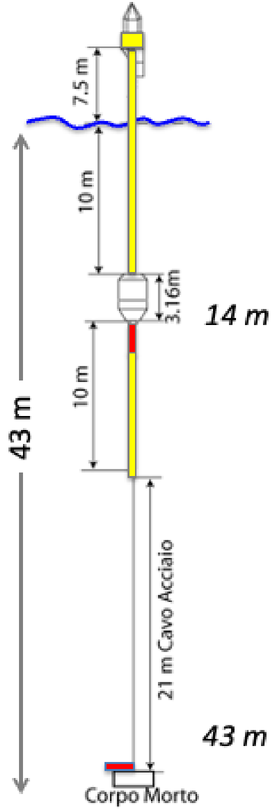
Early-Warning Flow Chart



Italian Civil Protection (DPC) Alert System



Position of the sirens at Stromboli



Source: M. Ripepe @ JRC-Ispra Workshop (2022)

World collaboration for Early Warning for All

More observations

Observations standardization

Data sharing globally

Source: WMO

Uncertainty on data and model outputs

HPC availability to run complex models

Integrated-holistic multi-hazard situational assessment for better risk informed early-action/warning